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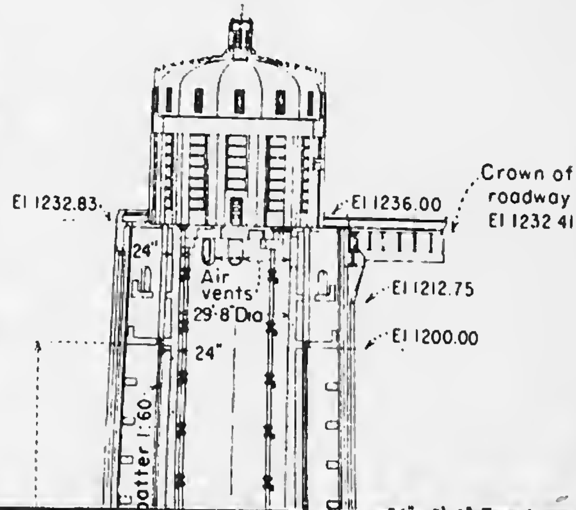
UNIVERSITY OF CALIFORNIA . DEPARTMENT OF ENGINEERING . LOS ANGELES, CALIFORNIA

EDUCATIONAL DEVELOPMENT PROGRAM

REPORT NO. **3-64**

HOOVER DAM

A CASE HISTORY IN ENGINEERING DESIGN



HOOVER DAM

A Case History in

Engineering Design

Report EDP 3-64, February 1964, edited by H. O. Fuchs for the Department of Engineering, University of California at Los Angeles, with support from the Ford Foundation. Reproduced with permission by the Stanford Engineering School with support from the National Science Foundation.

HOOVER DAM LOOKING UPSTREAM
(Courtesy of U.S. Bureau of Reclamation)

ECL 1-17

EDP Report No. 3-64
February 1964

HOOVER DAM

A Case History in Engineering Design

Peter Searls

One of a Series Edited by H. O. Fuchs

Department of Engineering
University of California
Los Angeles

PREFACE

This case history is one of a series intended for use in teaching engineering design.

The series is sponsored by the Educational Development Program of the Department of Engineering at the University of California, Los Angeles. The department has made funds from a Ford Foundation grant available for the preparation of this and other cases.

The material presented in this case history is drawn from publications and from interviews with G. M. Babcock, chief engineer for the Los Angeles Department of Water and Power; Lloyd Hudlow, former project manager at Hoover Dam, and Dee O. Towne, present project manager.

Illustrations were made available by the United States Department of the Interior, Bureau of Reclamation.

It is a pleasure to acknowledge the gracious cooperation of all these people.

January 1964
Los Angeles, California

Peter Searls
H. O. Fuchs

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1. U. S. Bureau of Reclamation, Boulder Canyon Project, Final Reports, Part IV, Bulletin 1.
2. California Colorado River Commission, Boulder Canyon Project.
3. U. S. Bureau of Reclamation, The Story of Hoover Dam.
4. U. S. Bureau of Reclamation, Boulder Canyon Project Final Reports, Part IV, Bulletin 2.

I. BACKGROUND

When plans for Hoover Dam first appeared on the drawing boards at the U. S. Bureau of Reclamation, the highest dam in the world was the Arrowrock Dam in Idaho, 348.5 feet high. The Croton Reservoir Dam in New York, at 300 feet, was considered "massive" and "monumental". Yet Hoover Dam was to dwarf these structures.

At the time of its completion, Hoover Dam was the largest concrete structure on earth, standing 726.4 feet high and containing over 3 million cubic yards of concrete. Greater than any of the pyramids of Egypt, Hoover Dam weighed over 5 million tons. More important, it led to the full use of the Colorado River.

A. The Need for Flood Control

Although the U. S. Army had made attempts to explore and map the river in the 1850's, the first topographic maps of the lower basin were not begun until 1901, the year after settlers began farming the newly irrigated lands in the Imperial Valley. Engineers of the U. S. Geologic Survey who explored and prepared the maps of the basin were well aware of the area's growing needs for water storage and flood control. They recommended over 70 dam sites along the river (see Figure 1). No one foresaw, however, the destruction the Colorado was soon to cause.

In 1905 and again in 1907 and 1909, floods breached the dikes beside the entrance to the Imperial Valley Irrigation Canal, destroying property valued at several million dollars and raising the level of the Salton Sea 270 feet.

In 1909, a Southern Pacific Railroad construction force succeeded in damming the flow by dumping thousands of tons of rock into the breach -- along with several railroad cars which fell in by accident. These efforts, which cost over a million dollars, saved the valley from becoming an inland sea and possibly prevented the river from undermining the cities of Yuma, Topock and Needles by back-cutting.

Silting soon became a problem in the Imperial Valley. It cost approximately 1.4 million dollars annually to keep the irrigation channel clear of silt so that water would not rise above the banks and flood neighboring farmlands.

Faced with these difficulties, the citizens of the lower Colorado Basin appealed to the federal government and, in 1920, the Kinkaid Act was passed, authorizing the Department of the Interior to look into the problems of the Imperial Valley.

LOCATION OF SOME OF THE EARLY PROPOSED DAM SITES
(Courtesy of U.S. Geological Survey)

FIGURE 1

B. The First High Dam Proposal

Two years before the act was passed, Arthur P. Davis, then director of the Bureau of Reclamation, had proposed construction of a dam of unprecedented height in Boulder Canyon. Davis' suggestion went largely unheeded outside the Bureau. Those who commented at all, scoffed at the idea as impractical and unsuitable to the needs of the Imperial Valley.

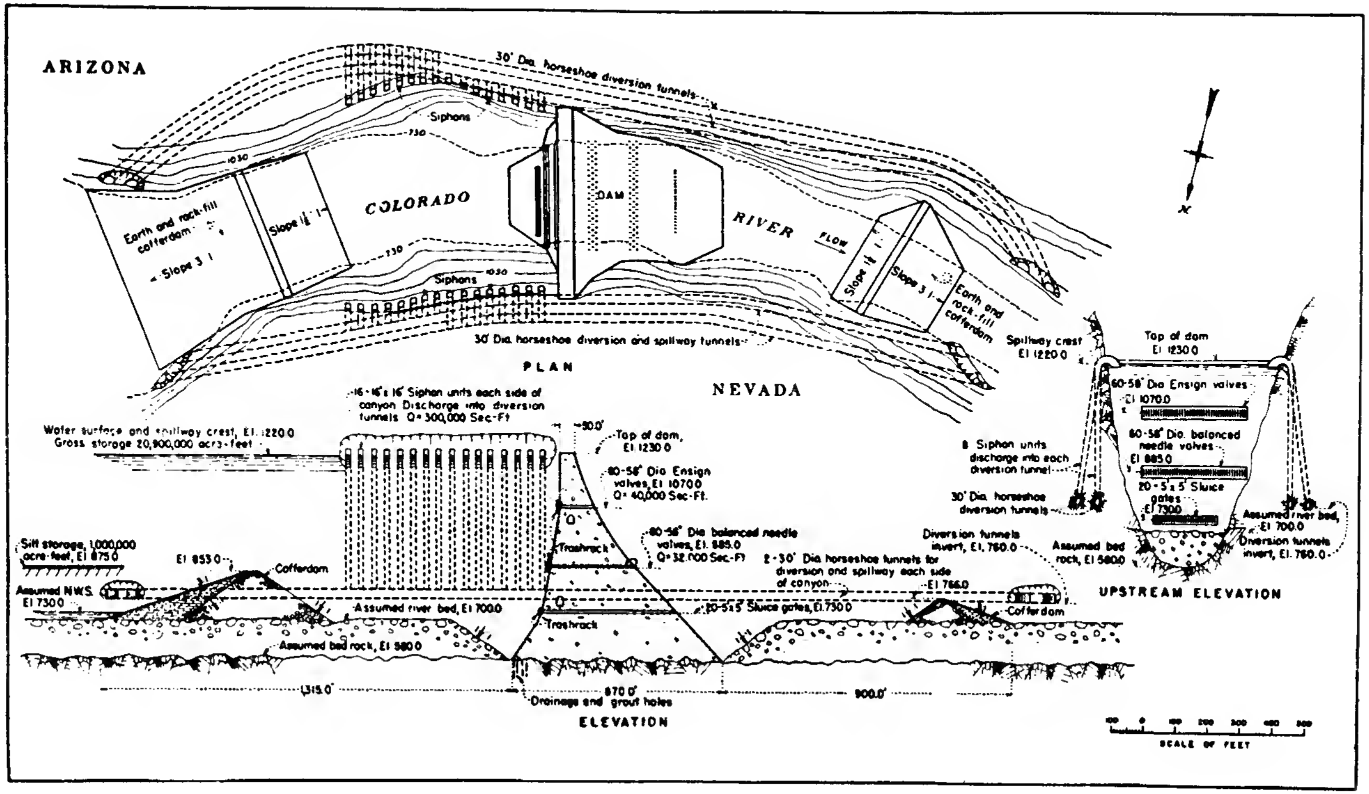
But Davis foresaw, over a year before preliminary survey work began, the scope, size and general site of Hoover Dam.

In 1919, the U. S. Geologic Survey and a party of Reclamation Survey engineers began intensive field investigations of the Black and Boulder Canyons. After passage of the Kinkaid Act, the departments increased their studies and from 1920 to 1923, Reclamation surveyors and engineers lived in the canyons, carrying out rock testing and topographic survey observations.

By this time, Davis' proposal had gained considerable support within the Bureau of Reclamation. A rough sketch (see Figure 7) for a high dam in the Boulder Canyon area was made in 1920. This sketch shows a straight concrete gravity dam, like the Arrowrock Dam with a cross section quite similar to that in the final plans. The straight line front slope in this early sketch is similar to that in the final plans (see Figure 8) especially when compared with the curved slope in intermediate drawings. Also the slope at the heel of the dam in both the 1920 and the final plans is at much the same angle, in contrast to the nearly vertical slope in intermediate plans.

The men who made these sketches and surveys survived tremendous hardships. Living in tents, with only the most primitive necessities, they endured temperatures as high as 125 degrees. Dr. Elwood Mead, the Commissioner of the Bureau of Reclamation during most of the development and construction of Hoover Dam, wrote that these explorations "involved coping with a river which, in the highest floods, rushed through the canyon with the speed of a railway train; of taking topography in more than 100 miles of canyon where precipitous cliffs 1000 feet high and of indescribable ruggedness had to be scaled. Three lives were lost in this hazardous undertaking. Every phase of the work involved great danger, but the dimensions of the possible dam and reservoir had to be known."

In 1922, Davis and Hubert Fall, Secretary of the Interior, were able to issue a preliminary report, based on this survey work, recommending construction of a high dam at or near Boulder Canyon.



EARLY DESIGN FOR DAM IN BOULDER CANYON.
A SKETCH MADE IN 1920 OF A STRAIGHT CONCRETE
GRAVITY DAM LIKE THE ARROWROCK DAM.
(Illustration Ref. 1, Fig. 14, p. 48)

FIGURE 2

This report was greeted with considerable skepticism, some calling the "high dam" totally unfeasible, while others accused the Reclamation Bureau of trying to increase its power in the federal government. But engineers at the Bureau's design office in Denver were already convinced that the dam could be built although little research had been done on the immense, complex problems of designing such a structure.

II. DEVELOPMENT

A. The Weymouth Report

In 1924, Frank Weymouth, chief Reclamation engineer, submitted an eight-volume report, containing data from the Fall-Davis report and later research. In his report, Weymouth listed seven possible dam sites, five in Boulder Canyon, two in Black Canyon.

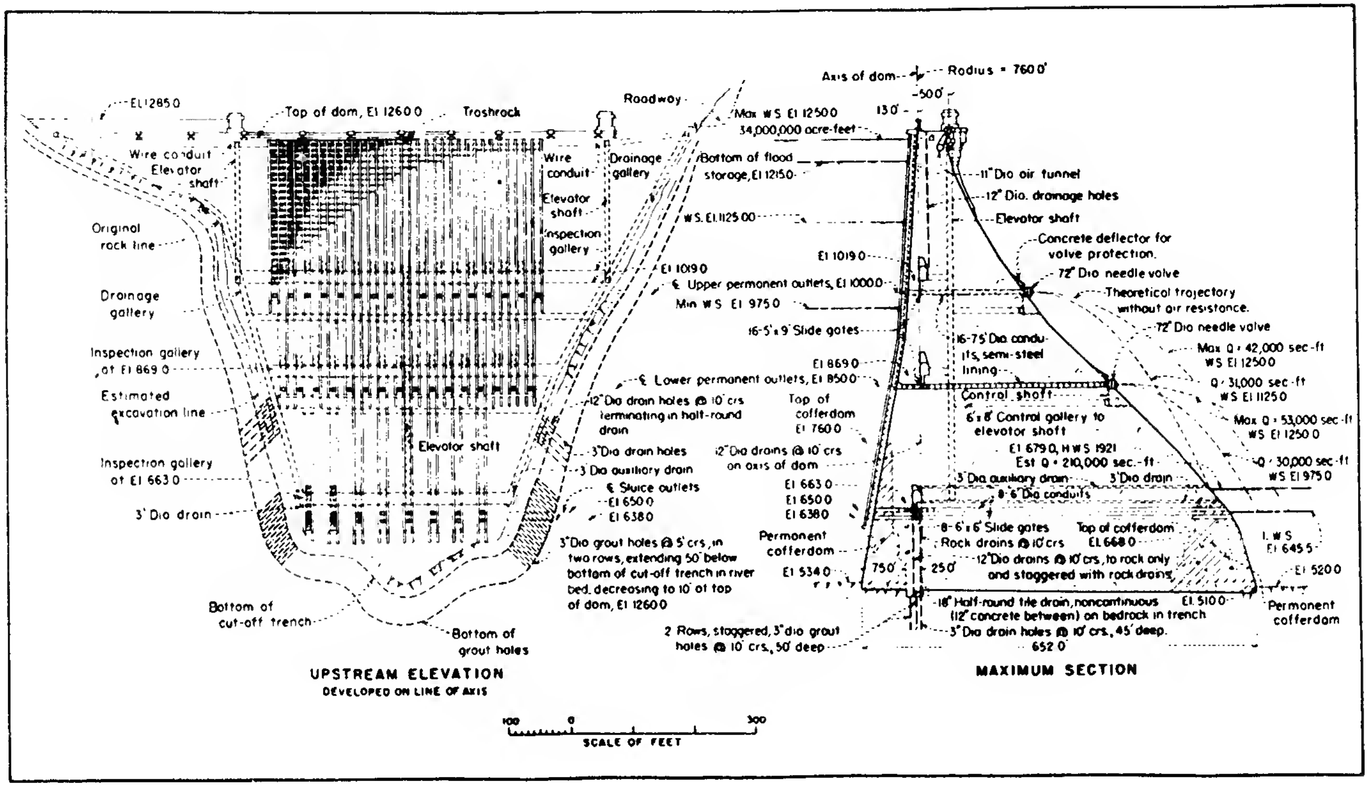
He also presented a general plan for a high dam (see Figure 3). This design, although more complex than earlier drawings, is still extremely simple compared to the final plans. Weymouth thought he could safely allow occasional floods to overtop his dam. However, this would probably have destroyed the dam and certainly have threatened the very areas the dam was supposed to protect. Weymouth made no provisions for producing electricity and he had the cofferdams forming the permanent toe and heel of the dam.

This feature was considered extremely dangerous, since cofferdams are temporary structures, designed only to keep the riverbed free of water while construction of the main dam is in progress. If permanent cofferdams were to fail, the entire project would be destroyed, threatening irrigation facilities and cities downstream. But if temporary cofferdams failed once the permanent dam had risen to a certain height, the permanent structure might well be able to withstand the floods.

The Weymouth report, supporting the "high dam", was one of four submitted to the House Committee on Irrigation and Reclamation. The reports of the U. S. Army Engineers and the Geologic Survey were neutral and Colonel William Kelly of the Federal Power Commission actively opposed the project. These reports started a four-year legislative battle.

B. Arguments Against the Dam

Most of the opposition to the Boulder Canyon project was political but several genuine objections were raised. Some critics said that a much smaller amount of masonry could hold an adequate reservoir at other sites and smaller dams could be completed more quickly and cheaply. The inaccessibility of the Black-Boulder Canyon sites was also criticized.



DAM SKETCH SUBMITTED WITH WEYMOUTH REPORT IN 1924
(Illustration Ref. 1, Fig. 15, p. 50)

FIGURE 3

Davis, however, maintained that the Black-Boulder Canyon site permitted greater flood control than sites upriver since it was just below the junction of several large tributaries to the Colorado (see Figure 4). The site had two advantages over downstream sites. It was deeper and, in Davis' words, "a deep reservoir of a given capacity with a moderate surface area will lose less water by evaporation and furnish more head for power than a broad, shallow reservoir."[1]

Its inaccessibility was also an advantage rather than a disadvantage since more accessible downstream sites contained developed property which would be destroyed by a reservoir "which although it might require only a small amount of masonry for its dam, requires a vast outlay for damages to cities, railroads, and other property, and costs about the same per acre-foot (of water) stored, besides destroying a great alluvial valley susceptible of high development."[2]

Davis pointed out that a reservoir of no more than 35 million acre-feet in his site would not inundate and prevent development of any other site. He maintained that a hydroelectric plant added to the project could pay off the investment, which he estimated at 43 million dollars, in about 40 years through the sale of power.

Davis countered the argument that smaller dams could be built more quickly by noting that the Black-Boulder Canyon area had been studied intensively for three years while no research at all had been made at any other site. He added that even after such study had been made, lengthy negotiations between the dam builders and property holders would probably follow before construction could begin.

A large, deep reservoir could handle silt better, Davis had said. It would lose less capacity, proportionally, than a small, shallow reservoir; and the Colorado carries more silt per year, 160 million cubic yards, than the amount of earth excavated in building the Panama Canal.

Some critics argued that too many unknowns would enter into the design of the "high dam." Stresses occurring within the dam itself were not fully known nor were the effects of heat generated by the immense mass of concrete as it hardened.

These arguments were countered by the development of the trial load method of analyzing arched-gravity concrete dams and by a unique method of artificially cooling concrete.

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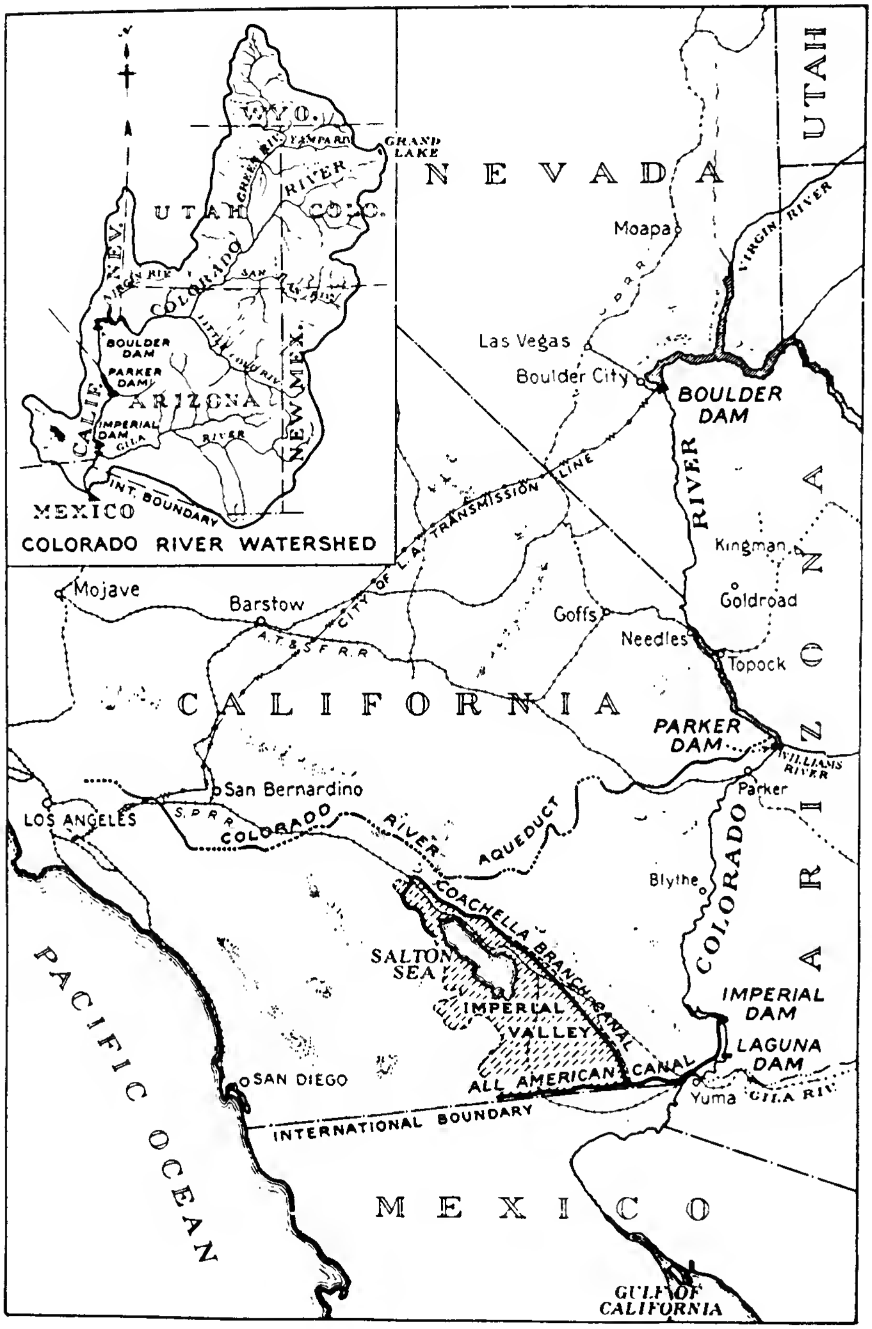
[1] Kelly, Col. William, et al., The Colorado River Problem.

[2] Kelly, Col. William, Ibid.



LOCATION MAP OF BOULDER CANYON PROJECT
(Illustration Ref. 1, p. v)

FIGURE 4

The trial load method[1], developed at the chief design office of the Bureau of Reclamation in 1923, enabled engineers to predict accurately the load distributions, deflections and stresses encountered in an arched-gravity dam.

A number of dam types had been suggested during the early research, but by 1925, the choice of concrete arched-gravity had been made, despite objections from several government engineers, including General George Goethals of Panama Canal fame. General Goethals favored a rock-fill concrete slab and estimated the cost of his dam at 60 million dollars against an estimated 49 million for the concrete arched-gravity. The arched-gravity type also had the advantage of deflecting much of the stress to the canyon walls which were hard enough in the Black-Boulder Canyon area to support such pressures.

C. Preliminary Designs

At the Denver office of the Reclamation Bureau, analysis and refinement of dam designs continued. Five dam heights, ranging from 570 to 605 feet, had been proposed. The engineers consulted water flow charts such as those shown in Figure 5 to find the largest possible reservoir. They were limited by two considerations:

(1) although almost all of the land to be covered by the proposed reservoir was federal property and largely undeveloped, too great a reservoir would have covered some lands already in use;

(2) too large a reservoir would have flooded upstream sites which could have been developed for power and/or water storage in the future.

Actual design could not begin until late in 1928, however, following Congress' creation of the Colorado River Board. The Board, aided by independent consulting engineers, chose the upper Black Canyon site from the seven recommended by Weymouth as the location for the dam.

"The Black Canyon site is more accessible," said the Board members in their report. "The canyon is narrower, the gorge is shallower below water level, the walls are steeper, and a dam of the same height here would cost less and would have a somewhat greater reservoir capacity.... The Black Canyon rock is not so hard to drill as that of Boulder Canyon; and it will stand better in large tunnel excavations with less danger to the workmen.

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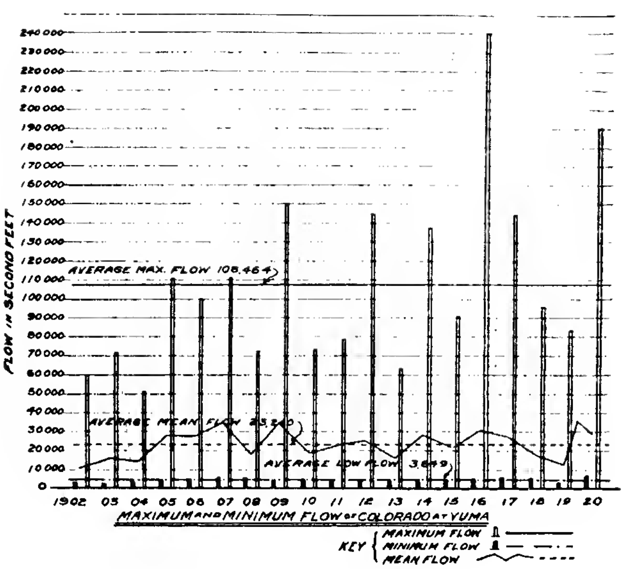
[1]For details on trail load method, see Part V of <u>Boulder Canyon Project, Final Reports</u>.



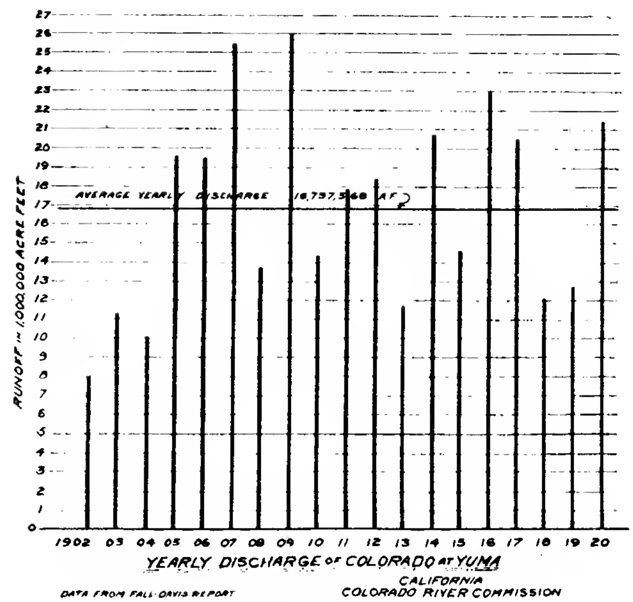


TABLE II

Discharge of the Colorado River at Yuma, Arizona

From Senate Document 142, 67th Congress

Year	Minimum flow Date	Minimum flow Second-feet	Maximum flow Date	Maximum flow Second-feet	Mean	Total discharge for year—acre-feet
1902	Oct. and Nov.	3,140	May	59,200	10,970	7,960,000
1903	Jan.	2,694	June	72,219	15,600	11,300,000
1904	Feb.	3,340	June	51,200	13,900	10,100,000
1905	Jan.	3,750	March	111,000	27,300	19,710,000
1906	Jan.	4,620	June	99,200	26,900	19,500,000
1907	Dec.	5,800	June	115,000	35,100	25,500,000
1908	Jan.	5,600	Dec.	72,500	18,900	13,700,000
1909	Dec.	4,100	June	149,500	35,800	26,000,000
1910	Oct.	4,300	May	70,300	19,700	14,300,000
1911	Jan.	3,700	June	78,300	24,600	17,800,000
1912	Jan.	3,400	June	144,000	25,300	18,400,000
1913	Jan.	2,600	June	62,500	16,200	11,700,000
1914	Jan.	3,300	June	137,000	28,500	20,700,000
1915	Sept.	2,700	Feb.	90,000	20,200	14,600,000
1916	Jan.	3,800	Jan.	240,000	31,600	22,940,000
1917	Jan.	5,300	July	143,000	28,400	20,600,000
1918	Sept.	4,100	July	94,300	18,100	12,150,000
1919	Jan.	1,800	Nov.	82,600	14,800	10,740,000
1920	Dec.	5,100	June	190,000	29,700	21,450,000
Average for 19 Yrs.		3,849	Av. for 19 Yrs.	108,464	23,240	16,797,368

WATER FLOW CHARTS AT YUMA USED AS ESTIMATES OF THE COLORADO'S DISCHARGE
(Illustration Ref. 2, pp 28 and 29)

FIGURE 5

"There is no doubt whatever but that the rock formations of this site are competent to carry safely the heavy load and abutment thrusts contemplated. It is well adapted to making a tight seal and for opposing water seepage and circulation under and around the ends of the dam." The report also noted that there was a good supply of building materials, such as gravel and aggregate, near the chosen site.

In December, 1928, the federal government passed the Boulder Canyon Project Act, authorizing the construction of Hoover Dam and directing the federal treasury to transfer 165 million dollars to the "Colorado River Dam Fund." From this fund Congress made appropriations as requested by the Secretary of the Interior.

The project was to provide flood and silt control, water for irrigation and other public use, and hydroelectric power, which the Secretary of the Interior would sell to pay the cost of building the dam and appurtenances.

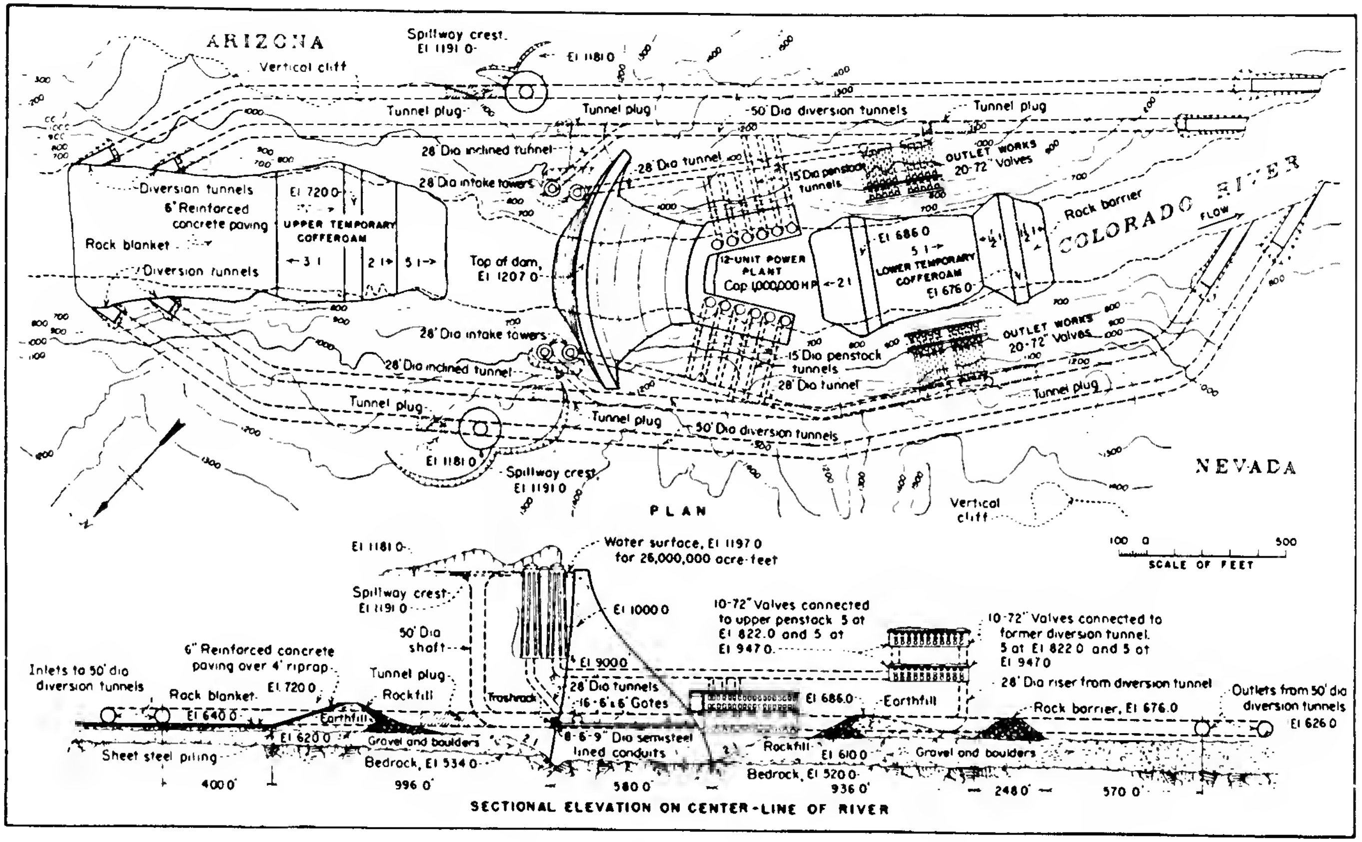
The Colorado River Board also drew up specifications for the dam which included, in addition to the power plant, a greater diversion tunnel and spillway capacity than that in earlier designs and a permissible stress allowance of 30 tons per square foot.

In earlier designs the river was to be diverted through three 35-foot tunnels with a total capacity of 100,000 second-feet. (A second-foot is one cubic foot of water flowing past a given point in one second.) However, floods of 300,000 second-feet had been recorded on the Colorado. Thus it was necessary to increase diversion tunnel capacity.

Also earlier designs had permitted stresses of up to 41.3 tons per square foot, but 30 tons per square foot was considered at that time the maximum safe stress allowance. However, subsequent research showed that mass concrete could handle up to 40 tons per square foot safely and it was found impossible to design the dam holding to the 30 ton limitation.

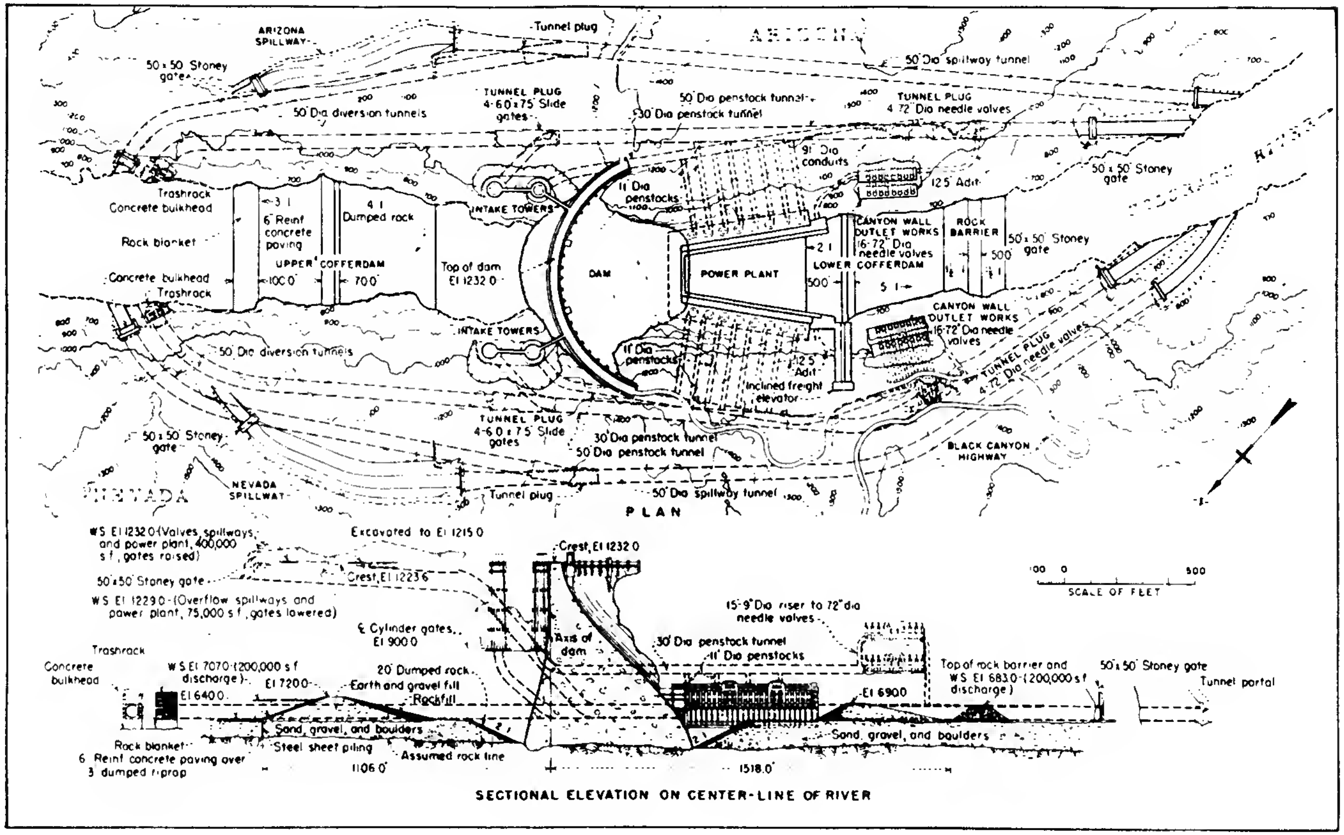
The Reclamation Bureau design office soon turned out the first drawings based on these new specifications and the definite choice of site (see Figure 6). Engineers continued working on the design, calculating load, stress and deflection at each point on the arches and cantilevers.

After the start of the Depression in September, 1929, President Hoover sent a memorandum to the Department of the Interior suggesting that construction begin as soon as possible to alleviate the widespread unemployment. Reclamation engineers increased their efforts and, often working late into the night, rushed the major part of the specifications to completion three months after receiving the memorandum and six months ahead of schedule.



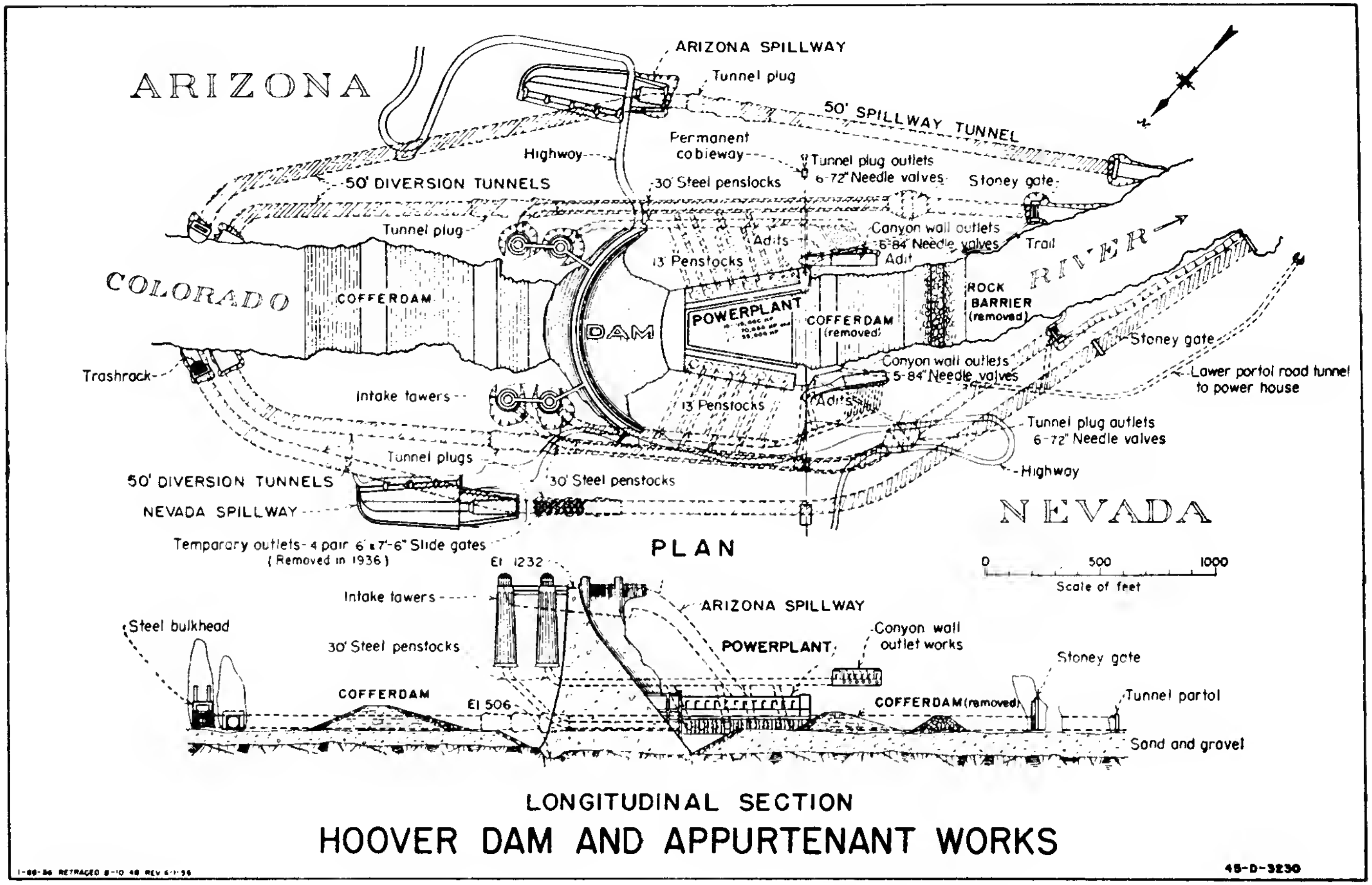
DESIGN FOR DAM MADE IN 1928 FOLLOWING INITIAL RECOMMENDATIONS OF THE COLORADO RIVER BOARD
(Illustration Ref. 1, Fig. 17, p. 53)

FIGURE 6



DESIGN FOR DAM MADE IN 1930 FOR REQUEST FOR BIDS ON LABOR CONTRACT
(Illustration Ref. 1, Fig. 18, p. 55)

FIGURE 7



FINAL PLAN FOR HOOVER DAM, 1931
(Illustration Ref. 3, p. 29)

FIGURE 8

The new design (see Figure 7), although used only in request for bids to build the dam, was an improvement over that made in 1928 in almost every respect. The alinement of intake towers and tunnels was closer. Side channel spillways with uncontrolled crests and open upstream ends replaced the circular vertical-shaft spillways in the 1928 drawings and the temporary sluices in the base of the dam were moved to the upstream plugs of the inner diversion tunnels to keep the dam free of all outlet conduits.

The 1928 plans had called for a dam 701 feet above bedrock (elevation above sea level, 1207 feet). This would have created a reservoir of 26 million acre-feet. However, the Colorado River Board soon decided to increase reservoir capacity to 30.5 million acre-feet to insure greater flood control. This necessitated raising the maximum water level from 1197 to 1222 feet above sea level and the overall height of the dam to 726 feet.

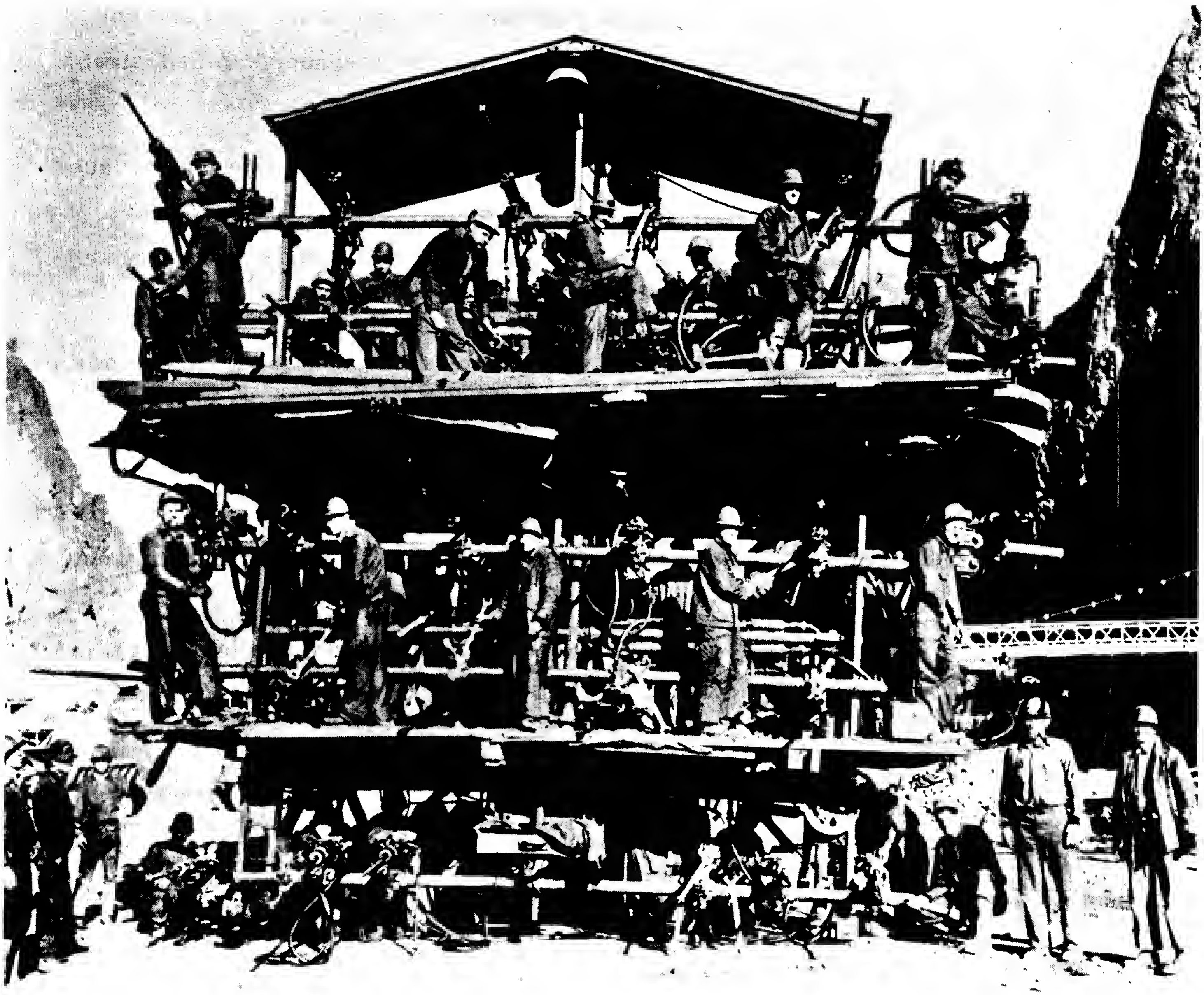
Many problems remained unsolved, however. The new plans placed additional concrete in the upper part of the dam and this created greater stress at the base. There were still right-angle pipe connections and vertical risers but these and other difficulties had to wait until the contract was let.

D. The Contract Award

In June, 1930, the Department of the Interior advertised for bids on the labor contract. Only three were submitted: Six Companies, Inc., of San Francisco bid $48,890,995.50, Arundel Corporation bid $53,893,878.70 and A. Guthrie and Company, $58,653,107.50. On March 11, 1931, the U. S. Government awarded its largest labor contract up to that time to Six Companies, a combine made up of the Utah Construction Co., the Pacific Bridge Co., Henry J. Kaiser and W. A. Bechtel Co., McDonald and Kahn, Ltd., Morrison-Knudsen Co., and J. F. Shea Co. Their bid was only $24,000 more than the cost estimated by the Reclamation Bureau and, considering the size of the undertaking, in remarkably close agreement.

For this sum Six Companies was to build the diversion works, the dam itself, outlet works, spillways and the power house. The government supplied all material to the contractor, purchasing in advance to avoid the possibility of a sudden rise in price. Due to changes in the design after the bid was let, the government revised its estimated labor costs to 54.7 million dollars. After certain deductions for services, such as electricity to Boulder City, the actual cash payment to Six Companies was 51.95 million dollars.

Each member of Six Companies had its construction speciality. Kaiser had concentrated on paving contracts. Both Bechtel and Morrison-Knudsen had experience in railroad, dam and general construction contracts.



TRUCK-MOUNTED FRAMEWORK FROM WHICH UP TO 30 DRILLERS COULD WORK
(Courtesy of U.S. Bureau of Reclamation)

FIGURE 9

Pacific Bridge, as its name implies, specialized in bridge building with emphasis on underwater construction and foundation work. The Utah Construction Co., although chiefly involved in railroad construction, had done considerable irrigation and reclamation work. McDonald and Kahn were general builders and J. F. Shea had paid special attention to tunnel work. Although the responsibility was not specifically divided among the constituent firms, Six Companies had experience in every type of construction necessary to the Hoover Dam project.

III. CONSTRUCTION

A. Preparation

As soon as the contract was awarded, Six Companies began collecting the immense amount of equipment and materials required to begin construction, spending about two million dollars in the process.

The Union Pacific Railroad built a 22-mile spur from Las Vegas to the site of Boulder City. In 1932 and '33 this spur handled more rail tonnage than any Western trunk line. A ten and a half mile railroad was laid from Boulder City to the edge of the Nevada canyon wall, interconnecting the sites of the various construction installations. Highways were built and electric transmission lines strung over the desolate, rugged terrain.

Six Companies constructed repair and maintainance shops and compressor plants. A tent camp mushroomed near the site of Boulder City. Men began stripping the canyon walls above the tunnel portals. A railroad trestle carried gravel from the Arizona pits eight miles upriver to the facilities on the Nevada side.

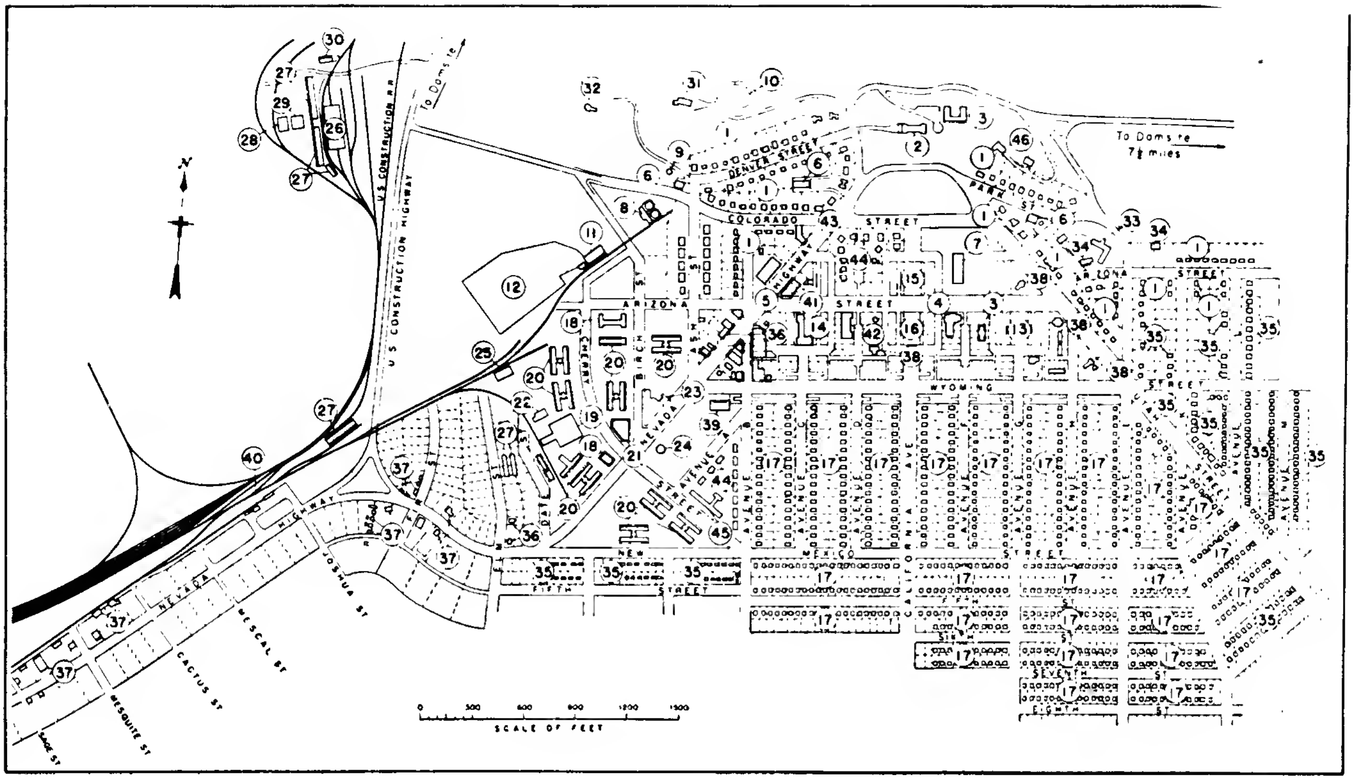
On July 4, less than four months after the contract was let, the first direct excavation began on the Nevada diversion tunnels.

B. The Final Designs

Meanwhile, in Denver the Bureau of Reclamation was carrying out detailed stress analyses and model tests on the proposed dam design.

Earlier model tests had been made with a rubber-litharge model of the dam Mercury was used in the model reservoir both to compensate for the added tensile strength of the rubber-litharge and to duplicate the weight of the water in an area much smaller than the scaled-down reservoir would have been.

However, in the final tests a plaster-celite compound was used to make the model and water was placed in a mock reservoir. This was found to duplicate more closely the actual conditions under which the dam would be built.



NUMBERS 1 TO 16 INCLUSIVE

BOULDER CITY

GOVERNMENT BUILDINGS AND RESIDENCES

1 - Residences
2 - Administration Building
3 - Dormitory
4 - Municipal Building
5 - Federal Garage and Fire Department
6 - Community Garage
7 - School
8 - Filtration Plant
9 - Receiving tank
10 - Water tank
11 - Government Warehouse
12 - Government Storage Yard
13 - Coronado Plaza
14 - Cardenas Plaza
15 - North Escalante Plaza
16 - South Escalante Plaza

NUMBERS 17 TO 34 INCLUSIVE

SIX COMPANIES, INC.

BUILDINGS AND RESIDENCES

17 - Residences
18 - Offices
19 - Mess Hall
20 - Dormitory
21 - Club House
22 - Laundry
23 - Six Companies Store
24 - Band Stand
25 - Garage
26 - R.R. Machine Shop
27 - Warehouse
28 - Carpenter Shop
29 - Layout Floor
30 - Oil Warehouse
31 - Executive's Lodge
32 - Superintendent's Residence
33 - Hospital
34 - Hospital Residences

NUMBERS 35 TO 43 INCLUSIVE

COMMERCIAL

PRIVATELY-OWNED BUILDINGS ON LEASED GROUND

35 - Residences
36 - Commercial Buildings
37 - Industrial Buildings
38 - Church
39 - American Legion Hall
40 - Los Angeles and Salt Lake Depot
41 - Hotel
42 - Theater
43 - Bus Terminal

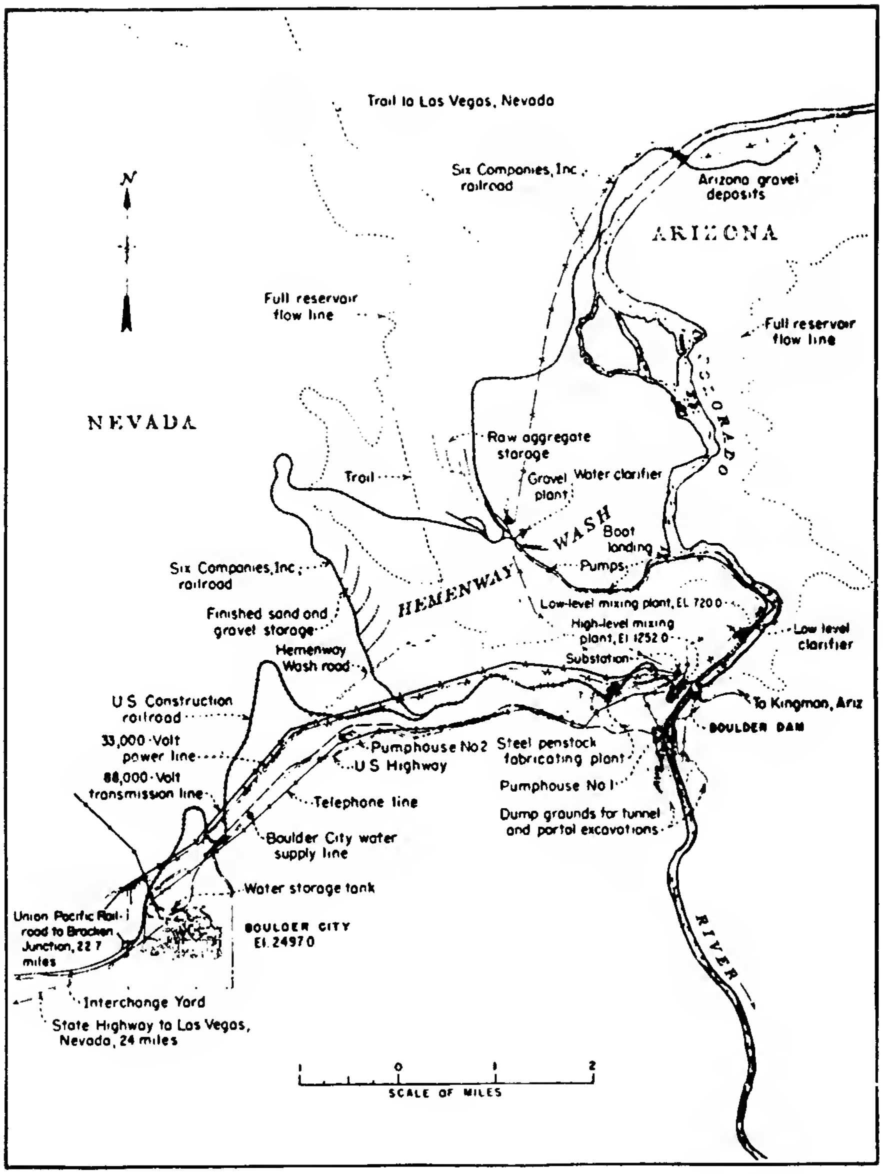
NUMBERS 44 TO 46 INCLUSIVE

BABCOCK AND WILCOX CO.

44 - Residences
45 - Dormitories
46 - Hillside Residences

PLAN OF BOULDER CITY
(Illustration Ref. 1, Fig. 27 and Key to Fig. 27, pp 72-73)

FIGURE 10



LAYOUT OF CONSTRUCTION FACILITIES
(Illustration Ref. 1, Fig. 32, p. 84)

FIGURE 11

The model tests showed that the additional concrete in the 1930 designs did not materially lessen the stress at the upper arches of the dam and actually increased stress at the lower arches. It also introduced an undesirable tension outwards toward the canyon walls.

Accordingly, the amount of concrete at the top of the dam was reduced as much as possible. In order to absorb the arch action of the upper part of the dam, long radius fillets were then added to the downstream face near the abutments.

Stress analysis also resulted in replacing the curved bulge at the downstream toe of the dam, which had appeared in all but the earliest sketches, with a straight line slope. (see Figure 8).

The temporary sluices, which had been moved to the inner diversion tunnels, had to be moved to the plug of the outer Nevada tunnel for construction purposes. Also, the upper set of canyon wall outlets was eliminated to simplify the design. The final plans were completed in the summer of 1931, about two months after construction had begun.

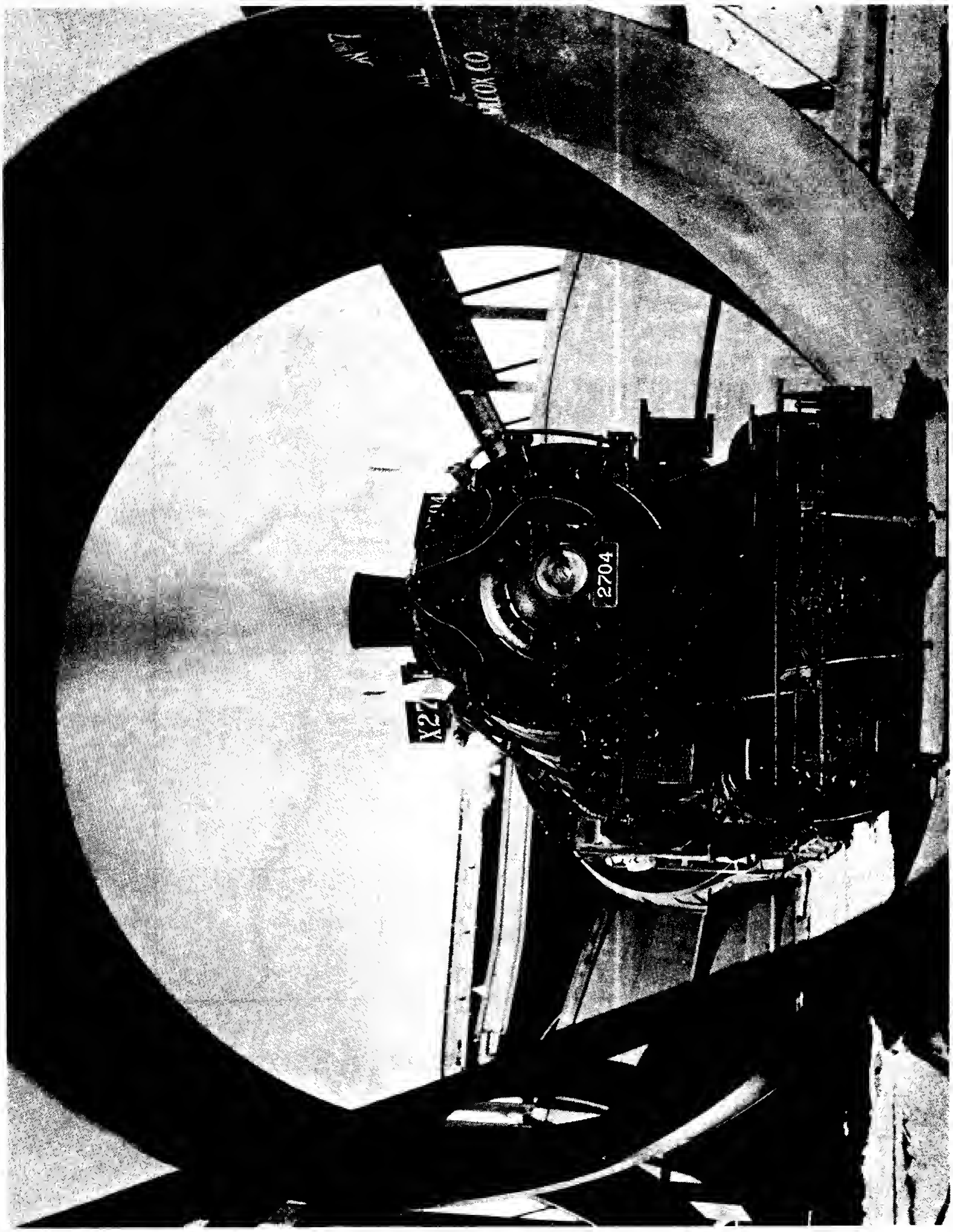
C. Further Preparation

The first task of the "Big Six", as Six Companies came to be known, was to dig four 50-foot diversion tunnels. This went slowly at first because drillers could work on only one part of the huge bore at a time. Then one of the construction engineers devised a truck-mounted framework on which 30 men could simultaneously drill the "shot" holes in which rock-blasting explosives were placed (see Figure 9).

Meanwhile, Six Companies was building Boulder City. At the peak of construction, the government and Big Six together employed over 5,000 men, all of whom, with their families, had to be housed. So Boulder City, a complete town with houses, streets, parks, schools, churches, stores, municipal and federal government buildings, was erected on a high plateau (see Figure 10).

While Boulder City was rising in the wilderness and crews bored tunnels through the canyon rock, Big Six was building a gigantic concrete mixing plant and Babcock and Wilcox, another contractor, erected a steel fabrication plant.

The concrete plant, designed and built at a cost of more than seven million dollars, included a gravel pit on the Arizona side, an aggregate classification plant, two concrete mixing plants and a cement blending plant (see Figure 11).



LOCOMOTIVE INSIDE PENSTOCK
(Courtesy of U.S. Bureau of Reclamation)

FIGURE 12

The unprecedented size of the penstocks -- 30 feet in diameter -- forced Babcock and Wilcox to build a steel fabricating plant at the site, as normal production and transportation facilities were inadequate (see Figure 12).

Meanwhile, Big Six also built five 20-ton temporary cableways spanning the gorge at strategic locations (see Figure 13). A number of smaller cableways were erected for special use and three derricks, two of 12-ton and one of 20-ton capacity were installed.

The diversion tunnels were nearing completion. Despite two floods which destroyed much electrical and drilling equipment, the tunnels were finished in November, 1932, over a year ahead of schedule.

The next task was building cofferdams to divert the river through the tunnels while dam construction was in progress. Temporary cofferdams were built at either end of the site by dumping loads of rock into the river, forcing it through the Arizona tunnels. The Nevada tunnels were closed at the time. The temporary dams were completed in 24 hours in November when the river was at its lowest flow and excavation on the regular cofferdam sites began as soon as the water over them was pumped out.

The upstream dam rose to a height of nearly 100 feet, the downstream one to nearly 70. They were constructed of rolled earth with steel and concrete reinforcement.

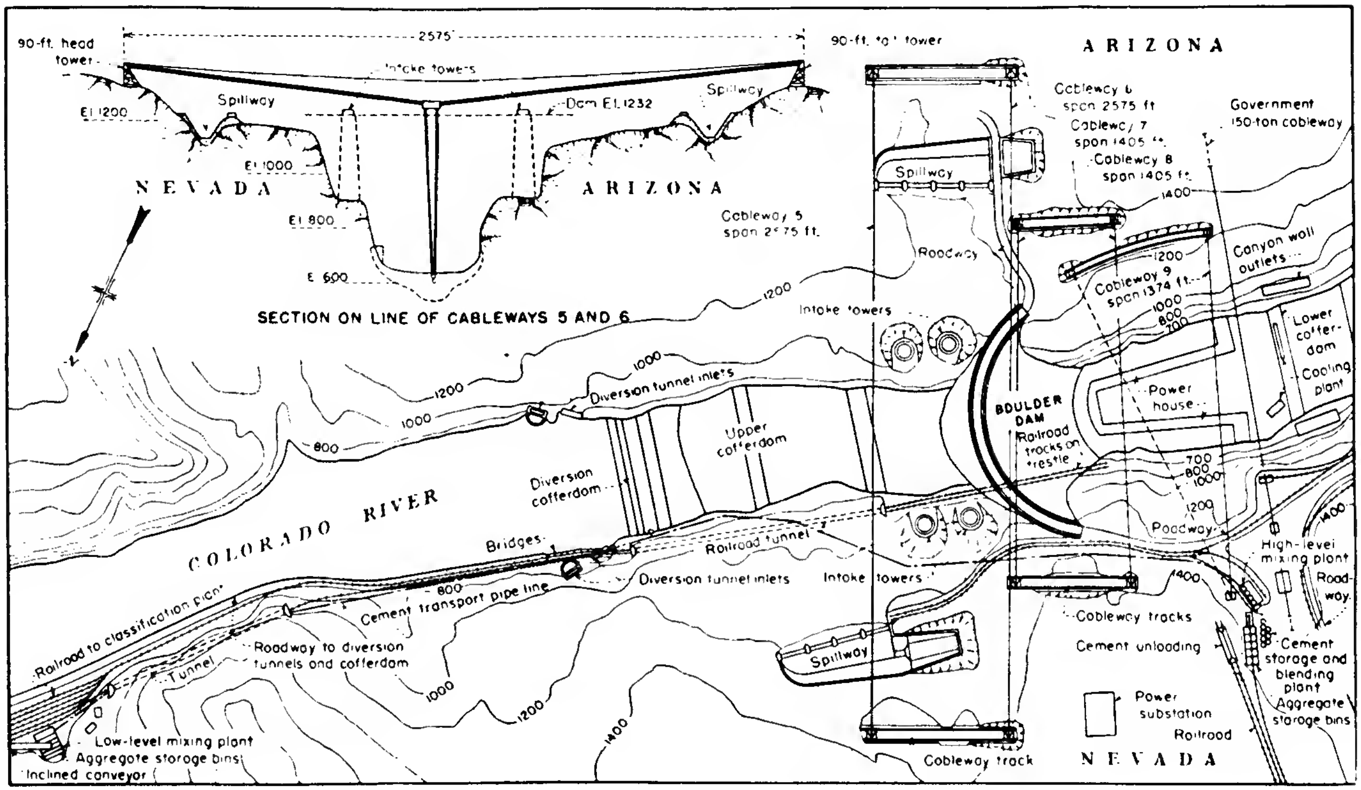
Meanwhile, the channel between the two dams was unwatered and the foundations for the main dam begun. Crews worked around the clock, excavating five feet to bedrock before the first forms for concrete were laid.

In anticipation of the spring floods three of the four diversion tunnels were opened.

D. Pouring the Dam

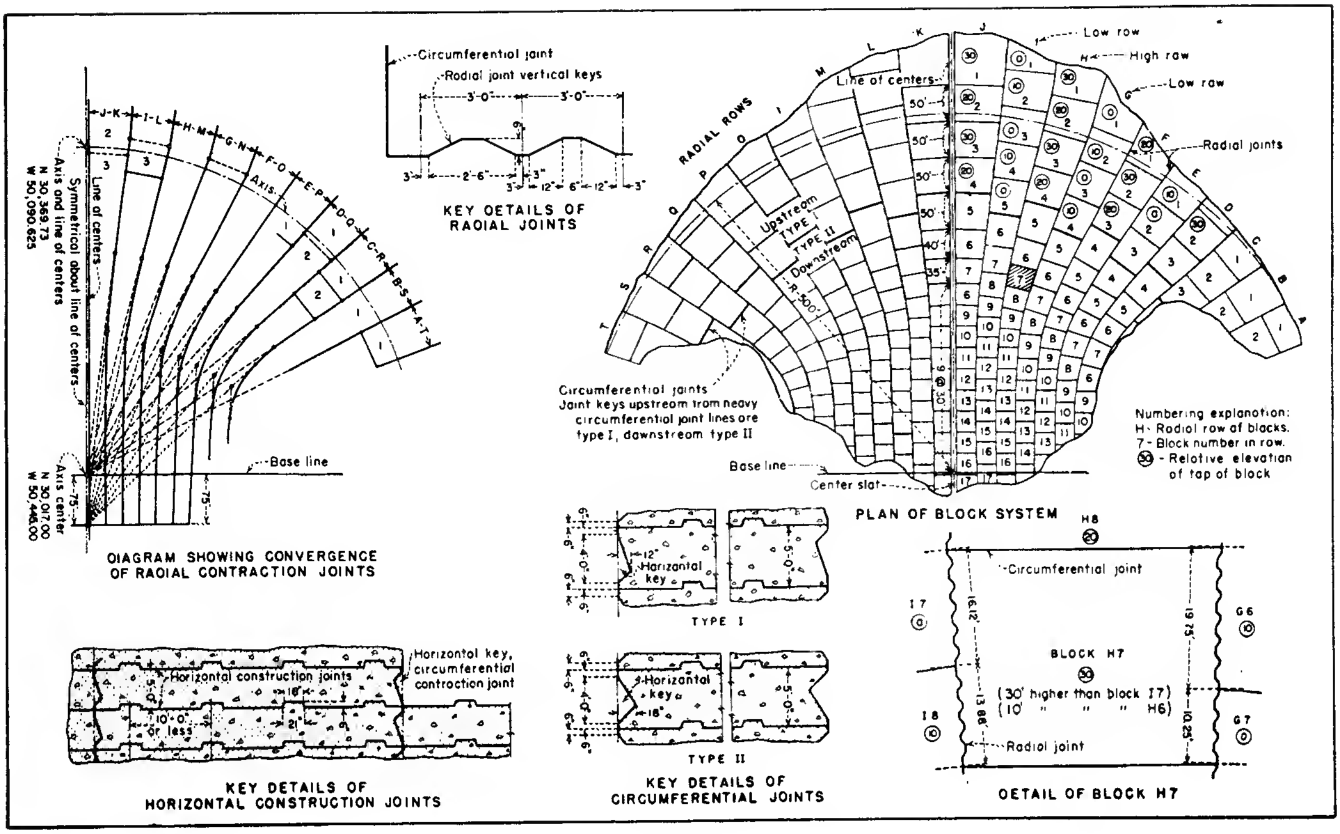
On June 6, 1933, the first bucket of concrete was poured. Prior to this, however, the Reclamation Bureau and consultant agencies had spent many hours studying the properties of mass concrete. From this study came two radical methods of handling concrete -- artificial cooling and arranging the concrete in blocks.

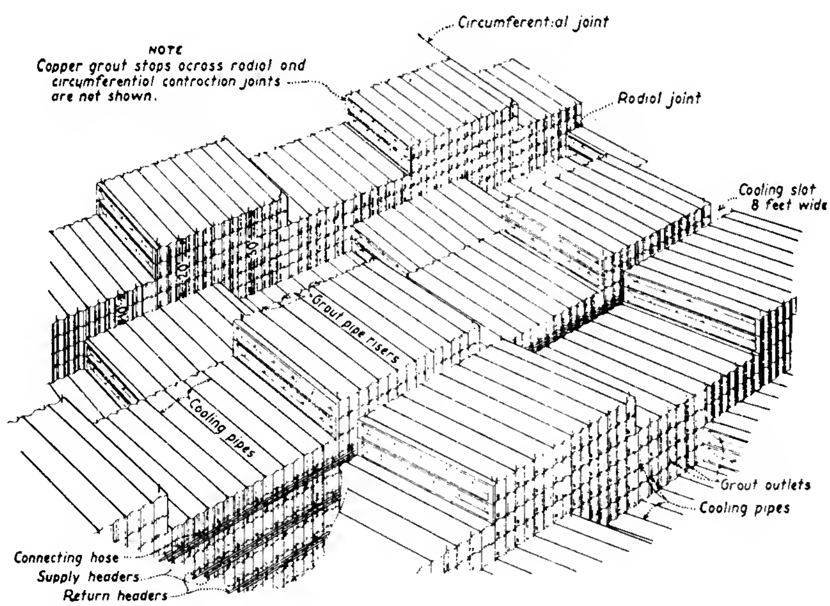
Concrete structures prior to Hoover Dam had been left to harden naturally. However, the heat created by five million tons of concrete hardening would have prevented the dam's settling for over 100 years. Meanwhile, it would have been ruined by unequal contractions and expansions. The engineers decided to counteract the high temperatures by setting an intricate arrangement of cold water pipes in the concrete. After the concrete was in the forms, air-cooled water was circulated



LOCATION OF TEMPORARY CABLEWAYS ACROSS GORGE
(Illustration Ref. 1, Fig. 42, p. 102)

FIGURE 13





BLOCK LAYOUT SYSTEM AND RELATIVE ELEVATION OF BLOCKS DURING CONSTRUCTION
(Illustration Ref. 4, Figs. 4 and 5, pp 34 and 35)

FIGURE 14

through the pipes, followed by refrigerated water. Workers placed 431 electrical resistance thermometers in the blocks, checking temperatures so the cooling process could be stopped at the right time. When the blocks had set, the pipes were filled with grout, a thin cement used for sealing cracks and fissures.

The heat problem solved, the engineers next had to find a way to control cracks due to shrinkage in cooling. In arch dams prior to Hoover Dam, radial joints (running roughly at right angles to the curve of the arch) had been sufficient to control cracking. But it was necessary to provide both radial and circumferential joints in the new dam, thus dividing it into blocks which looked like a mass of prismoidal columns during construction (see Figure 14) The size of the blocks was limited since blocks too large would crack while cooling and ones too small would not contract enough to leave room for the grout which would seal the dam.

The blocks between any two continuous radial joints appear from the top like a wedge driven toward the downstream face. The stress created by the weight of the water at the upstream face is directed forward to all the blocks in the row and each block directs a certain amount of stress out toward the canyon walls and down to the river bed.

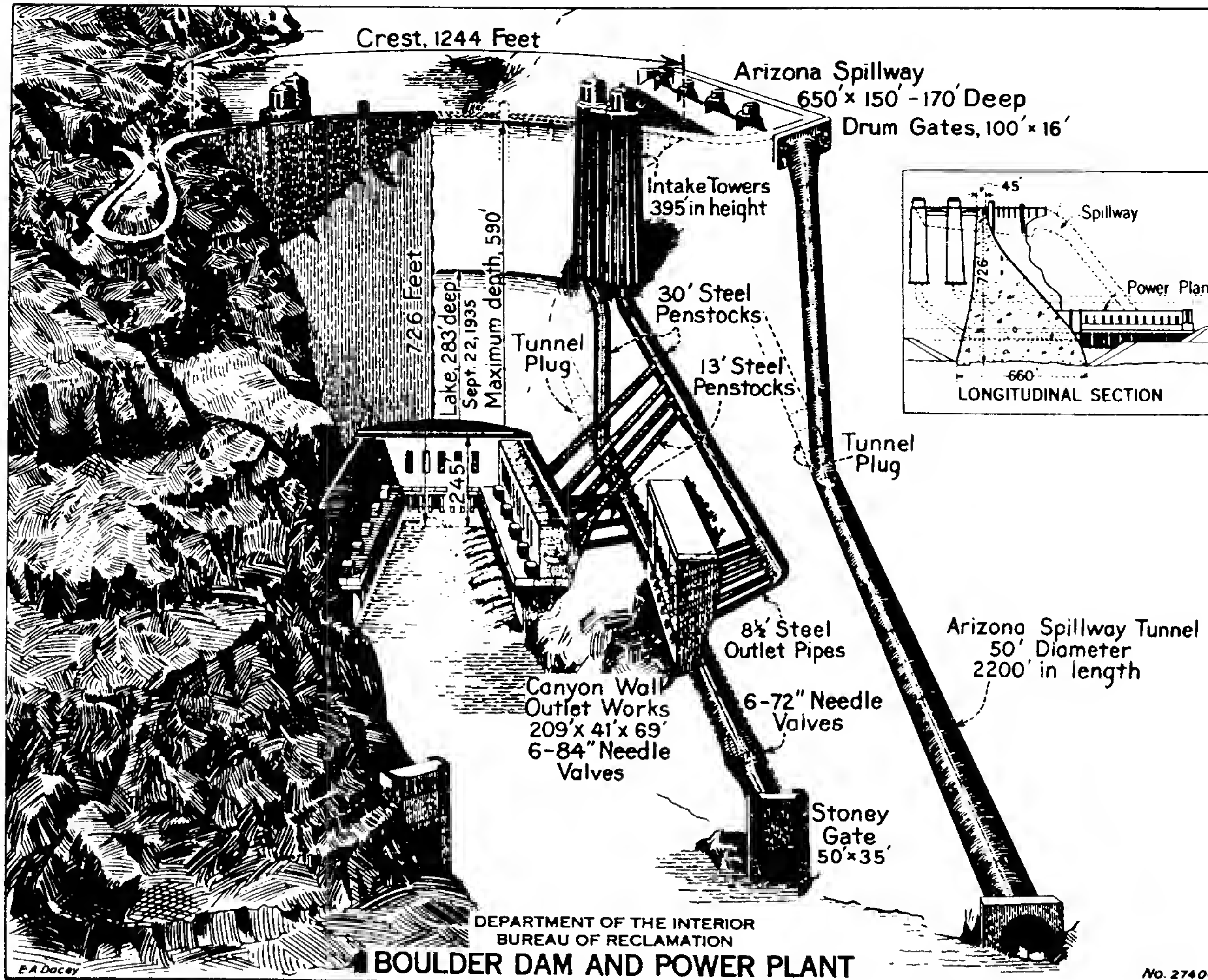
The circumferential joints are staggered to prevent side slipping with horizontal keyways to prevent slipping up or down. The keyways at the radial joints were vertical to prevent blocks from slipping toward the downstream face.

Crews placed the last of the 3 1/4 million cubic yards of concrete in May, 1935, over two years ahead of schedule. Only the intake towers, penstocks, spillways and the powerhouse remained.

E. Mechanical and Electrical Equipment

The four steel-reinforced concrete intake towers -- two on each side of the river -- were set on rock shelves carved from the canyon walls. Their bases are about 385 feet above the floor of the reservoir to keep silt and sediment from running through the power plant or spillways. The towers are 395 feet high and about 75 feet in diameter. There are two cylindrical gates, 32 feet in diameter and 11 feet high, in each tower, one near the bottom, the other about half-way up. Both are protected by heavy steel trashracks which keep any heavy debris from floating into the towers and jamming the tunnels. The gates are raised by an electric hoist at the top of the tower.

Each tower controls one fourth of the water flowing through the electric plant's generators. The two upstream towers are connected by 37-foot penstocks (narrowing to 25 feet) to the inner diversion tunnels. These have been plugged with concrete about one third of the way from



This drawing illustrates the manner in which Boulder Dam works. The Nevada wall of Black Canyon is shown as solid, whereas the Arizona wall is cut away to reveal the intake towers, the spillway, the penstock pipes, and outlet works. Inside the Nevada wall of the canyon a similar set of diversion works has been placed. Principal dimensions are shown.

LAYOUT OF INTAKE TOWERS, PENSTOCKS AND SPILLWAYS
(Illustration Ref. 3, p. 28)

FIGURE 15

their original inlet (see Figure 15). These tunnels contain 30-foot steel pipes from the intake towers to the power plant and 25-foot pipes to the canyon wall outlet works.

The downstream towers are connected by 37-foot diameter tunnels (again narrowing to 25 feet) to the power plant penstocks and the outlet works.

The outer diversion tunnels were plugged with concrete about half-way from their openings. The lower ends are connected to spillways at the top of the dam controlled by drum gates. They have been used only once, in 1941, when the reservoir was full.

The power house was completed in 1936. It is a U-shaped structure with an unusual roof -- built to withstand the impact of a one-ton boulder falling from a height of 200 feet.

The first generator began producing power on October 26, 1936, and, with the installation of the final generating unit in 1962, there are now 17 turbines in the Hoover power plant with a total rated capacity of 1,850,000 horsepower, able to produce 1,344 megawatts of electricity (1,344,800 kilowatts).

Annual gross generation at the Hoover power plant has averaged 4.3 billion kilowatt hours during the past 15 years ending at May 31, 1963. General Regulations under the Boulder Canyon Project Adjustment Act provide that the amount of yearly firm energy will be decreased by 8,760,000 kilowatt hours each year. This provision makes allowance for depletion in stream flow resulting from upstream developments.

IV. OPERATION

A. General

Experience in operating Hoover Dam and the power plant has confirmed the judgment of the Reclamation Bureau design engineers in all but a few minor respects.

Despite earthquakes, which seem to be caused by filling and emptying the reservoir, the dam has developed no cracks or other flaws. According to Lloyd Hudlow, former project manager at Hoover Dam, "the tremendous weight of water on the old river bed seems to cause considerable shifting. The last quake shows movement in all directions laterally as well as up and down, and it was felt as far away as Las Vegas. The quakes usually come shortly after the high and low water marks in the reservoir."

The power house has withstood the elements as well as the dam has. Recently a rock weighing between 15 and 20 tons fell from a height of 70 feet onto the powerhouse roof rupturing the lower layer of roof concrete. However, no power generating equipment was damaged.

There have been few problems in regulating the reservoir although the closing of the Glen Canyon Dam upriver and the attempt to fill that reservoir has caused Lake Mead to fall to a very low level.

"We know how much capacity we have for incoming flood storage", Hudlow said. "We also get reports from the upper watershed. These aren't completely accurate; there are a lot of variables. How dry was the ground the snow was covering? It might absorb water which will show up at a later date. We might not have warm precipitation. The longer the snow lays on the ground, the more evaporation, or to be more precise, the more sublimation. Downstream we've got unpredictable events, too. A large water order can be shut off by a cloudburst."

Hudlow points out that low water means a cut in the power output since water orders from farmers downstream must be filled first.

There have been minor modifications in the spillways and penstocks to reduce cavitation, a pitting caused by the action of water flowing over concrete or metal surfaces, but the only real modifications have taken place in the intake towers.

B. Intake Towers

Originally the towers were designed so that the upper gates would be used when the reservoir was high enough. However, Hudlow noted that using these gates created several problems:

(1) a large percentage of salts was left in the lake;

(2) colloidal silt coming down the river collected around the lower gates when the upper ones were used;

(3) the upper gates let warmer water through, especially during the summer, and this adversely affected the fish life in the lower Colorado.

The lower gates are thus used most frequently although once a month the upper gates are opened while the lower ones are closed. Then the lower gates are opened and the upper gates closed.

The use of the lower gates has led to several modifications. The motors raising and lowering them have been speeded up so that it now takes 10 minutes to raise them instead of an hour as formerly.

Also the lip on the inside of the gate was removed. Water flowing across the surface of this lip created a vacuum pulling the gate down and setting up a self-excited vibration. Removal of the lip reduced the surface area and eliminated the vibration.

C. The Power Plant

Operation of the power plant has generally been good. According to G. M. Babcock, chief engineer of the Los Angeles Department of Water and Power, which operates approximately two thirds of the generating equipment at the dam under an agency contract with the U. S. government, the troubles with the plant have been relatively minor and common to all hydroelectric plants. Cavitation in the turbine runners and tape separation in the generator coil windings have been the chief difficulties but normal maintainance keeps them in check. The tape separation has not been enough to cause failure at several times the maximum current flow according to Dee O. Towne, present project manager.

Towne also observes that the predicted silt problem has not materialized. "Silting has turned out to be the least of our worries since Glen Canyon now traps about 60 percent of the silt in the Colorado."

The only other difficulties are created by the highway across the top of the dam and inadequate tourist facilities.

Hoover Dam has drawn an increasing number of vacationers since 1945 and attendance records are set almost every year. Parking is limited, the highway over the dam is only two lanes wide and the elevators which carry observers into the bowels of the dam are barely adequate for the flow of tourists both foreign and American.

It would appear that the engineers of the U. S. Bureau of Reclamation were altogether too modest in assessing the public recognition their feat would inspire.

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